DIRECT NUMERICAL SIMULATION OF OPEN-CHANNEL FLOW IN THE FULLY ROUGH REGIME

Mazzuoli Marco[12] & Uhlmann Markus [1]
[1] *Institut für Hydromechanik, Karlsruher Institut für Technologie (KIT), Karlsruhe, Germany*
[2] *Department of Civil, Chemical and Environmental Engineering (DICCA), University of Genoa, Genoa, Italy*

Abstract The Direct Numerical Simulation (DNS) of an incompressible open channel flow over a layer of rigid spherical roughness elements fixed on the wall in well-packed square arrangement has been performed which shows values of the Reynolds number $R_b \sim 6900$ ($k_s^+ \sim 100$) and produces a mean velocity defect $\Delta U^+ \sim 7$ in the range of the fully-rough regime. First and second moment statistics of the velocity field have been analyzed. The stress distribution as well as the hydrodynamic force and torque acting on the surface of individual roughness elements have been computed. Results are presently shown and compared with those obtained in the context of a previous DNS performed in the transitionally rough regime.

SUMMARY

The present contribution is aimed at providing additional insight into the interaction between turbulent open-channel flow and rigid particles fixed on a plane bottom. This knowledge is required by a number of engineering applications (environmental engineering, chemical industry, turbomachineries, bio-fluid dynamics) and is fundamental to formulate reliable predictions of the amount of sediments mobilized at river beds or along hill-slopes. Recently DNS of a transitionally rough open-channel flow for a value of the bulk Reynolds number Re_b of approximately 2900 has been performed [1, 2]. The roughness consisted in rigid spherical roughness elements arranged on a plane bottom with a square pattern (see figure 1a). In [2] the existence of spatial and temporal correlation and cross-correlation of the force and the torque acting on individual roughness elements has been investigated. That work has been presently extended to the case of fully rough open-channel flow.

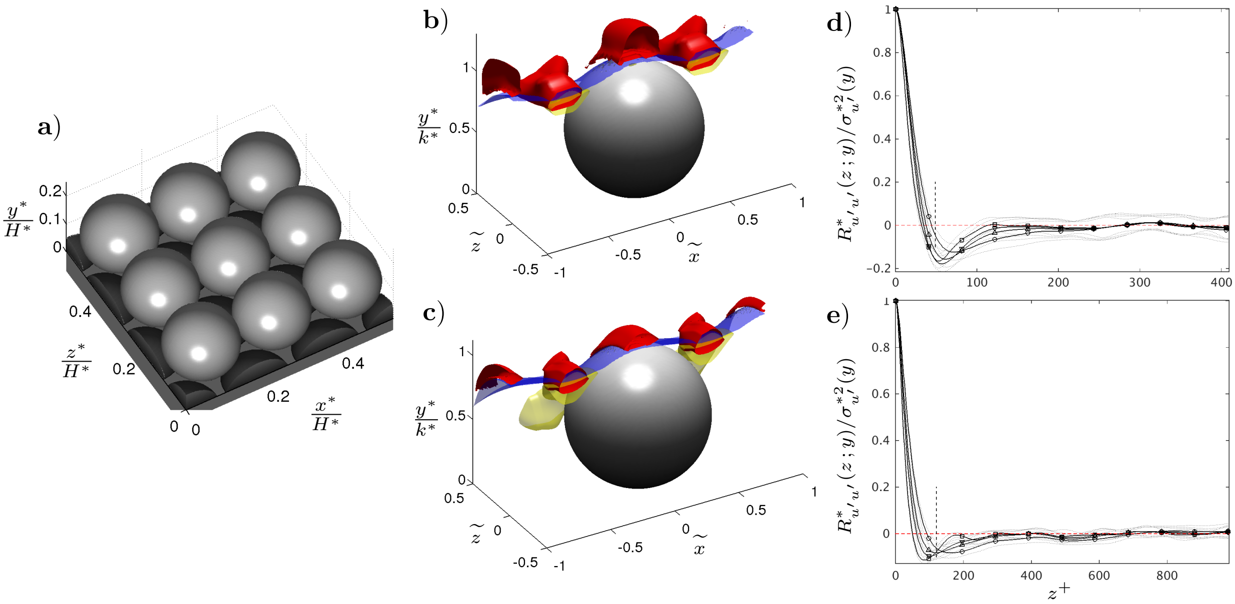

Figure 1. a) Configuration of a portion of the channel bottom which was implemented in simulations F50 and F120. Flow is directed towards the positive x-axis. b) and c) show the structure of the time- and particle-periodic-averaged flow field for simulation F50 and F120, respectively. Yellow and blue isosurfaces identify $u'^+ = -0.2$ and $u'^+ = +0.2$, respectively. Red surface detects vortex structures with the λ_2-criterion ($\lambda_2^* = 0.006 u_\tau^{*4}/\nu^{*2}$). Coordinates $\widetilde{x}$ and $\widetilde{z}$ denote the streamwise and spanwise coordinates normalized by k^*, with origin shifted into the center of a sphere. d) and e) show the normalized two-point correlation functions of u'^* along the spanwise direction for simulation F50 and F120, respectively. Symbols identify correlation lines related to different distances from the wall: $y^* = 0.18H^*$ (squares), $y^* = 0.20H^*$ ($\bigtriangledown$), $y^* = 0.22H^*$ ($\bigtriangleup$), $y^* = 0.25H^*$ ($\bigcirc$). Vertical dashed line indicates the spanwise-spacing of spheres which equals the size of the roughness k^+.

The bed configuration schematized in figure 1a has been used. The numerical method is as described in [4] which employs an immersed boundary technique to force the no-slip condition at the surface of the roughness elements. The computational domain of size $12H^* \times H^* \times 3H^*$ in the streamwise, wall-normal and spanwise direction, respectively, was discretized by a uniform grid of grid-spacing $\Delta x^+ = \Delta y^+ = \Delta z^+ = 1.13$ (i.e. $H^+ = 651$). Let the DNS performed by [2] in the transitionally rough regime and the present DNS in the fully rough regime be hereafter indicated by F50 and F120, respectively, while the symbol * will denote dimensional quantities.

Figure 1b-c shows the structure of the flow field averaged both over particle-periodic boxes and in time, the red iso-surface identifying the vortex structures (sliced by a vertical plane for the sake of clarity). In the case F120 (figure 1c) vortices develop over the crest of the spheres which are closer to the sphere surface than in the case F50. Moreover, wide low-speed regions (yellow iso-surface) form downstream of the spheres as well as along the streamwise-oriented grooves between spheres. The root mean square of the streamwise velocity fluctuations, $\max[u'^*_{rms}(y)]$, computed at distance y from the bottom, shows the maximum value at the distance from the virtual wall $(y - y_0)^+ = 18$ in both the F50 and F120 simulations (figure not shown here), y_0^+ denoting the distance in wall-units of the virtual wall from the bottom. In the case F50, however this distance is well above the crest of the roughness elements while in the latter case it is located below the crest. The spanwise two-point correlation of the fluctuations of the streamwise velocity (indicated with $R_{u'u'}(z;\, y)$ in figure1d-e) computed at distance y^* from the bottom, shows that low- and high-speed streaks, oriented along the streamwise direction, are present in the vicinity of the crests of the spheres. In particular, the maximum correlation is obtained at $(y^* - y_0^*)$ equal to $0.2H^*$ and $0.18H^*$ for the cases F50 and F120, respectively, and corresponds to the spanwise distance between low- and high-speed streaks $\lambda_z^+ = 57$ and $\lambda_z^+ = 90$, respectively. The phenomenon of the modulation of λ_z was already known in the context of channel flows over streamwise-oriented riblets and is presently supposed to be caused by the regular arrangement of the spheres. Figure 1d-e also shows that the velocity fluctuations tend to be less correlated in the roughness sublayer in the case F120 than in the case F50. This might be related to the fact that, by increasing Re_b, roughness elements penetrate the flow more deeply, thereby promoting the homogenization of turbulence in the near-wall region.

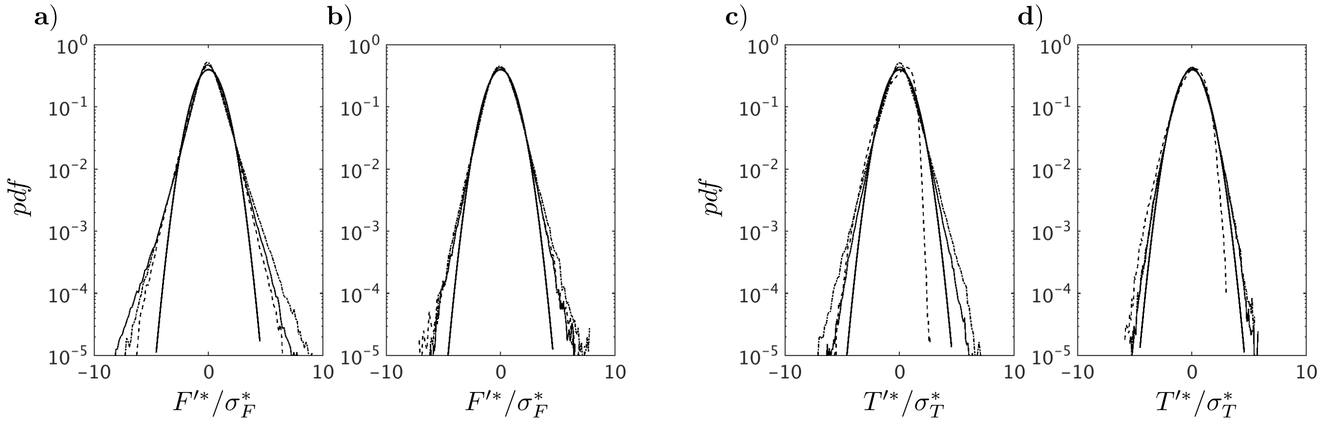

Figure 2. PDF of fluctuations of force (a,b) and torque (c,d) for the cases F50 (a,c) and F120 (b,d). $F_x'^*$ and $T_x'^*$ are indicated by solid light lines, $F_y'^*$ and $T_y'^*$ by dashed lines, $F_z'^*$ and $T_z'^*$ by dotted lines. σ_F^* and σ_T^* denote the standard deviations of force and torque. Solid heavy line indicates the Gaussian distribution.

Finally, force and torque instantaneously acting on individual roughness elements have been computed. In the case F120, the lift coefficient (based on the vertical-lift force values averaged both over time and over 1024 roughness elements) was found 24% larger than in the case F50. Moreover, by increasing the Reynolds number, the Probability Density Functions (PDFs) of the fluctuations of drag (F_x'), vertical-lift (F_y') and lateral-lift (F_z') tend to collapse on the Gaussian distribution as much as the PDFs of the torque related to the corresponding axes (T_x', T_y', T_z') (see figure 2). This effect results from the reduction of the ratio of the viscous length scale to the roughness size with increasing Reynolds numbers. As a result, force and torque are expected to develop more smoothly in the fully rough regime than in the transitionally rough regime. The possibility for the particles to be displaced by the hydrodynamic force will be inferred from a work-based approach ([3]).

References

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